Baryons and Their Halos

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Abstract. Galaxies are composed of baryonic stars and gas embedded in dark matter halos. Here I briefly review two aspects of the connection between baryons and their halos. (1) The observed baryon content of galaxies falls short of the cosmic baryon fraction by an amount that varies systematically with mass. Where these missing baryons now reside is unclear. (2) The characteristic acceleration in disk galaxies correlates strongly with their baryonic mass surface density. This implies a close coupling between the gravitational dynamics, which is presumably dominated by dark matter, and the purely baryonic components of galaxies.

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INTRODUCTION

Our current cosmological paradigm envisions cosmic structures like galaxies being embedded in extended halos of cold dark matter. Enormous progress has been made in simulating the growth of large scale structure in the dark component [1]. Forming actual galaxies in simulations, by which I mean the baryonic components we can observe, has proven to be rather more difficult.

A wide gulf exists between our theoretical notions about how galaxies should be and our observational picture of how they are. Most of the problems stem from the connection between the dark matter and the harder to simulate baryons. Here I discuss two of the outstanding issues.

THE BARYON CONTENT OF DARK MATTER HALOS

The early universe was a highly uniform mix of photons, dark, and baryonic matter with a cosmic baryon fraction $f_b = 0.17$ [2]. As dark matter halos form, baryons are supposed to condense within them to form luminous galaxies [3]. I would naively expect the cosmic fraction of baryons to be retained by each and every dark matter halo. We can therefor test this hypothesis by making an accounting of the baryon content of individual dark matter halos.

Such an inventory has recently been assembled [4]. The basic result, which has long been apparent [5], is that most of the expected baryons are missing (Fig. 1). Not only do we suffer form a dynamical missing mass problem (for which we invoke CDM), but we also suffer from a missing baryon problem. This is distinct from the global missing baryon problem in which the sum of known baryons falls short of the density expected from Big Bang Nucleosynthesis [6]. Here, individual objects are missing baryons on a halo by halo basis.
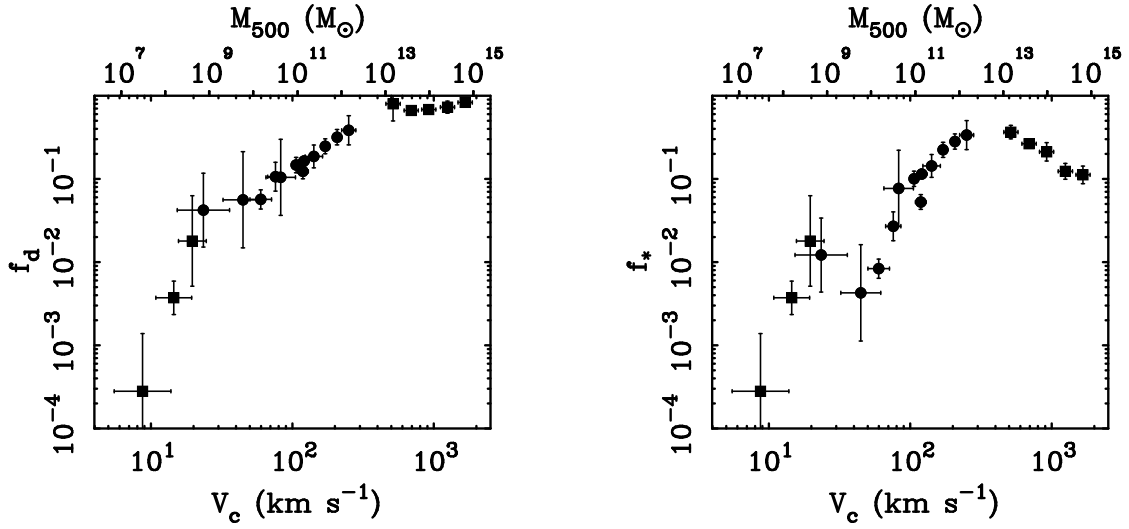
FIGURE 1. The fraction of the expected baryons that are detected [left: $f_d = M_b/(f_b M_{500})$] and the fraction converted into stars [right: $f_* = M_*/(f_b M_{500})$] as per [4]. The detected baryon fraction increases monotonically with mass while the stellar fraction peaks between $M_{500} = 10^{12}$ and 10^{13} M$_\odot$.

An obvious question, then, is where are all these missing baryons? The most popular idea seems to be that they are in undetected hot gas that has failed to cool and condense into galaxies or was blown away by supernova feedback. The first place one would expect to find such baryons is in the halo: away from the central galaxy but still mixed in with the dark matter halo. This does not appear to be the case, however, as direct searches do not find the required mass [7, 8].

It may be possible that feedback has liberated many baryons entirely form their parent halos. Indeed, the retained baryon fraction strongly correlates with potential well depth (Fig. 1). It seems natural therefor to invoke mass-dependent feedback in order to explain the observed trend. However, getting the numbers right remains a huge challenge. Even the most sophisticated simulations involving feedback [9, 10], beautiful as they are, fail by an order of magnitude. In the particular case of [9, 10], roughly half the baryons are retained at a scale where only about 5% are observed.

HALO-BARYON COUPLING

Dark matter provides the dominant total mass of a galaxy. Within the optical radius, dark matter appears to dominate in some types of systems, like low surface brightness disks [11] and Milky Way satellites [12]. In high surface brightness spiral and elliptical galaxies, baryons appear to play a dynamically important role in the inner parts [13, 14]. However, there is a deeper issue than the degree to which baryons contribute to the gravitational potential [15]. It is understanding the palpable coupling between the two components [16, 17].

Fig. 2 plots the characteristic acceleration against the baryonic surface density for a sample of spiral galaxies [18]. The characteristic acceleration is taken to be the
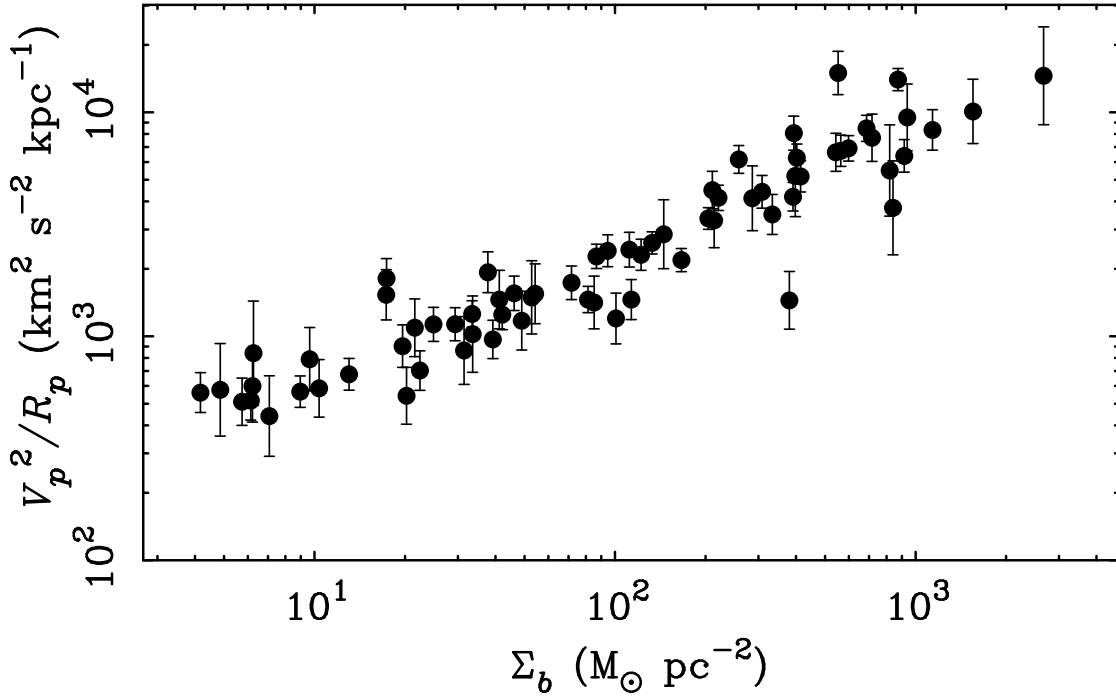
FIGURE 2. The characteristic acceleration of disk galaxies as a function of their baryonic surface mass density. The strong correlation is a clear indication of a coupling between baryonic and dark components: the two "know" about each other [16, 17].

centripetal acceleration measured at the point were the contribution of the baryons peaks. For a purely exponential disk, this point is at $R_p = 2.2$ scale lengths [19]. No approximation is made here; the peak radius R_p is taken at the actual maximum of the mass model, including both the bulge and stellar and gaseous disks [20]. If dark matter dominates throughout, then the acceleration measured at this point is dominated by the halo and should not depend on the baryonic surface density.

The characteristic baryonic surface mass density is the central surface density of the exponential disk that is equivalent to that which the actual baryonic mass would have if bulge, stellar, and gaseous disk were all arranged into a single exponential distribution [20]. In order to include the gas mass, it is necessary to assign some mass-to-light ratio to the stars. For specificity, we use the stellar population models of [21] here. The choice of stellar mass estimator is not critical. A different choice would merely translate the abscissa, modulo the gas surface density. The basic relation is already apparent with raw surface brightness [22].

Contrary to the expectation for complete dark matter domination, the observed *dynamical* acceleration correlates strongly with observed *baryonic* surface density. Clearly the baryons do matter to the dynamics. Indeed, the baryonic surface density is predictive of the total gravitational potential due to both dark and baryonic mass. This is true not only at the specific location illustrated in Fig. 2, but at all radii in disk galaxies [17]. Thus Renzo's rule: *"For any feature in the luminosity profile there is a corresponding feature in the rotation curve and vice versa"* [16].

We remain very far from being able to reproduce the observed coupling between dark and luminous matter in galaxy formation simulations. Indeed, this strikes me as a serious fine-tuning problem for any ΛCDM model. In this context, I find it disturbing that the only theory to have correctly predicted the observed behavior *a priori* is MOND [23].

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